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On the width of the giant resonance in photonuclear reactions

By SVEN A. E. JOHANSSON

With 2 figures in the text

SUMMARY

A compilation has been made of the width of the giant resonance in photonuclear reactions. The experimental material is discussed and it is shown in which cases the measured cross-section curves represent tho total photonuclear absorption. It turns out that the non-deformed nuclei have a rather constant width. The width of the deformed nuclei is larger and shows considerable fluctuations. The theoretical implications of these facts are discussed.

Introduction

It is well known that the cross-section curves of photonuclear reactions have a characteristic shape with a giant resonance, which corresponds to absorption by electric dipole transitions. This giant resonance has been interpreted in various ways. The collective models explain the resonance as due to collective oscillations of the nucleus. In the single particle models the resonance is explained as a group of strong single particle transitions.

Regarding the width not very much can be predicted from the theoretical models. In the collective models the width is determined by the damping of the collective oscillations but it is very difficult to calculate this effect accurately. Recently it has been pointed out by Okamoto (1) and Danos (2) that the giant resonance in deformed nuclei should be splitted up in two components giving a broader resonance. In the single particle model the width is determined partly by the energy differences between the single particle transitions and partly by the width of the single particle states. On this basis it is expected that nuclei with a magic number of protons or neutrons should have an especially narrow resonance. It has been claimed by Nathans and Halpern (3) and by Yergin and Fabricand (4) that this is actually true.

In recent years the photonuclear cross-section curves of many elements have been measured. It seems worth while to discuss this experimental material from the point of view of the width of the giant resonance. The purpose of the present paper is to make a compilation of the measured values and to relate it to the various models proposed for the photonuclear absorption.

The selection of the experimental data

In selecting the experimental data one encounters several difficulties. The measurements are of different types and have been made in different ways. It is therefore necessary to establish some objective rules for the selection.

First of all there is the difficulty that the photonuclear absorption is never measured directly. The measurements give the cross sections for the various partial reactions (γ,n), (γ,p), (γ,d) and so on. These cross-section curves need not have the same shape as the cross-section curve for the photonuclear absorption. They are determined by the competition between all the possible reactions, which depends on threshold values, level densities and barrier penetration. In discussing the mechanism for photon absorption, however, we are mainly interested in the cross section for the total photonuclear absorption. It can in principle be obtained by adding the contributions from all the various partial reactions. This is not a practical way, however, since for most nuclei only one or at most two of these reactions have been studied. Furthermore, there is the difficulty of adding two cross-section curves which have been obtained by different methods and often in different laboratories. The systematic erorrs are not the same and this is very likely to cause a broadening of the resulting curve. In the present discussion the cross-section curve of the predominant reaction is therefore used to obtain a measure of the width of the giant resonance. This has also been done in the few cases in which the cross sections for more than one reaction are known. Only such cases have been accepted in which the cross section of the predominant reaction is known or estimated to be at least $^2/_3$ of the total cross section. The cross-section curves for the main reactions (γ,n) and (γ,p) are known to be rather similar. The predominant reaction should therefore rather well represent the total absorption.

Another serious difficulty arises from the fact that cross-section curves for the same element measured in different laboratories do not agree. The reason is that the cross-section curves are not measured directly. They are calculated from the measured yield curves but then the shape of the bremsstrahlung spectrum must be known. This is, in general, not known very well; in most cases some theoretical spectrum has been used. Variations in spectrum shape then can cause the differences between the curves from different laboratories. This problem has been discussed by Katz and Goldemberg (5). They compare the curve for tantalum measured in three different laboratories. Similar comparisons can be made for several other elements as well. It then turns out that there is a systematic difference in the width of the giant resonance. One can correct for this effect by normalizing the values of the width so that values for the common elements agree as well as possible. This has been done in the present discussion. It must be emphasized, however, that this correction is rather small, of the order of 5 %. The conclusions of the present discussion do not depend on this correction. It should make the experimental material more uniform, however.

Most cross-section curves have been determined by detecting the emitted neutrons or protons. In the case of an element with more than one isotope the resulting curve will be a superposition of the curves for each isotope. These curves are in general somewhat different and the measured curve will be broader than the curves for each isotope. The discussion has therefore been limited to elements having one single isotope or one predominant isotope. When the cross section is determined by detecing the induced radioactivity, there is of course no such limitation.

The earlier cross-section measurements were naturally rather crude and do not agree very well with more recent ones. To get a more uniform material only the latest measurements have been used.

The experimental data

The rules that have been outlined in the preceding section have been used to select the data for the present discussion. They have been selected from the measurements reported in references 3–10.

For the medium and heavy elements the $[\gamma,n]$ reaction is predominant. For the elements above calcium the (γ,n) cross-section curves have therefore been used. For the light elements the situation is more complicated and it is necessary to discuss each nucleus separately.

The nuclei of the type $A = 4n$ with $n = 3 - 10$ form a rather uniform group. It has been shown both theoretically (11) and experimentally (12) that the cross section for the (γ,p) reaction is considerably greater than the cross section for the (γ,n) reaction. Hence the (γ,n) measurements for these nuclei cannot be used for the present discussion. The (γ,p) cross section is known only for C^{12}.

Other nuclei, like Li^7, N^{14} and F^{19}, have a very low (γ,np) threshold. This reaction should therefore be very important, perhaps predominant. The cross-section curves, which have been determined by neutron detection, include both the (γ,n) and the (γ,np) cross sections. They should rather well represent the total cross section.

Both the (γ,n) and (γ,p) cross sections have been measured in Be^9. The (γ,n) cross section is considerably larger and hence it has been assumed to represent the total cross-section.

For Na^{23} only the (γ,n) cross section is known. One can estimate, however, knowing the thresholds and level densities, that the (γ,p) reaction has approximately the same integrated cross section. The (γ,n) curve has therefore not been included in the present discussion.

Both the (γ,n) and (γ,p) cross sections have been measured in Al^{27}. The latter one is the largest. The measured (γ,p) curve also includes part of the (γ,np) reaction. Hence it has been taken to represent the total cross section.

The photonuclear reactions in P^{31} should be similar to those in Al^{27} since thresholds and level densities are similar. Hence the measured (γ,n) curve cannot be used for the present discussion.

It would be of great interest to include data for the heavy elements thorium and uranium. The difficulty is that fission gives an important contribution to the total cross section and that the threshold of the $(\gamma,2n)$ reaction is very low. Recently, however, Gindler *et al.* (10) have made a careful determination of the cross section for (γ,n), $(\gamma,2n)$ and $(\gamma$, fission). The curves were measured with the same machine and with similar techniques. The systematic errors should therefore be the same. Hence the total cross section has been taken as the sum of the curves for the three partial reactions.

The analysis of the data

The width of the giant resonance is usually defined as the full width at half maximum. This choice introduces some difficulties, however. Most of the data are (γ,n) curves obtained by neutron detection. These curves include the $(\gamma,2n)$ cross-section with the double weight, since two neutrons are emitted in each reaction. This causes a broadening of the upper half of the giant resonance. The width will therefore depend on the threshold and cross section of the $(\gamma,2n)$ reaction. This is especially disturbing since there is a systematic trend in the $(\gamma,2n)$ cross-section. For magic numbers the $(\gamma,2n)$ threshold is high and the cross section small. Between magic numbers the threshold is lower and the cross section larger. This introduces an artificial broadening of the giant resonance in the regions between magic numbers.

Another difficulty with the usual definition is that the upper half of the resonance is not very well defined. The experimental procedure for determination of cross-section curves makes the errors very large in this region. This can easily be seen by comparing different determinations of the same cross-section curve. They usually agree well in the lower half but deviate considerably in the upper half (see, for example, Fig. 4 in ref. 3).

In the present discussion these difficulties have been avoided by defining a "width" as the energy difference between the maximum point and the lower half-maximum point. This requires of course that the maximum point is fairly well defined. This seems to be the case, most curves have a rather sharp peak.

One of the objectives with the present investigation is to find out if there is any correlation between the width of the giant resonance and the nuclear deformation. Okamoto (1) has tried to find such a correlation by calculating the deformation from the spectroscopically measured quadrupole moments. Such a procedure is open to some objections. The experimental errors for the quadrupole moments are very large. Even more disturbing is the fact that for light and medium heavy nuclei the quadrupole moment to a large extent is a single particle effect and not a collective effect. In order to calculate the deformation one has to know the projection operator, which is well defined only in the strong coupling approximation. Okamoto concludes, for example, that the nuclei V^{51}, Co^{59} and In^{115} have a large deformation. These nuclei are almost magic and one would not expect them to be deformed.

In the present work another criterion for nuclear deformation is used. Alder *et al.* (13) show that the transition to a stable deformation for an even-even nucleus occurs when the energy of the first excited state has the value

$$E = 13\frac{\hbar^2}{\mathfrak{J}},$$

where $\mathfrak{J}$ is the moment of inertia about an axis perpendicular to the symmetry axis for a rigid spheroid of mass AM. For even-even nuclei this criterion has been applied directly. For odd A nuclei an interpolation has been made between the neighbouring even-even nuclei.

Results

The width has been measured on the curves selected as described above. Table 1 and Fig. 1 shows the result.

The figure has several interesting features. There is a very pronounced dip at $A = 90$ corresponding to $N = 50$. This region has been especially investigated by Yergin and Fabricand (4). They interpret this dip as a narrowing of the giant resonance due to the closing of the neutron shell. There are, however, considerable difficulties with such an interpretation. Among the strontium isotopes Sr^{88} with $N = 50$ has the broadest resonance and Sr^{86} with $N = 48$ the narrowest. Another disturbing fact is that other nuclei with magic nucleon numbers do not seem to have any especially narrow resonance. This is true for V^{51} with $N = 28$, La^{139} with $N = 82$ and lead with its major isotope having $Z = 82$ and $N = 126$.

There is an interesting relation between the width of the resonance and the threshold for the (γ,n) reaction among the nuclei around $N = 50$. Zr^{90} has the

Table 1. The width of the giant resonance (see the text for the definition of the width). When two measurements exist for the same nucleus the mean value is listed. The data are normalized as described in the text to get the best possible agreement between different laboratories.

Nucleus	Width, Mev	Reference	Nucleus	Width, Mev	Reference
Li^7	4.5	5	Y^{89}	1.4	4
C^{12}	1.0	6	Zr^{90}	1.3	4
N^{14}	1.9	9	Zr^{91}	2.6	4
F^{19}	4.0	9	Zr^{92}	2.6	4
Al^{27}	3.2	6	Nb^{93}	2.7	7, 8
Cr^{50}	2.4	5	Rh^{103}	3.2	8
Cr^{52}	2.4	5	In^{115}	2.7	7
V^{51}	2.5	5, 8	I^{127}	2.5	7. 8
Mn^{55}	4.0	7, 8	La^{139}	2.5	7, 8
Fe^{56}	3.5	7	Ta^{181}	3.2	7, 8
Co^{59}	2.4	7, 8	Au^{197}	2.4	7, 8
As^{75}	3.5	7, 8	Pb^{208}	2.3	7
Sr^{86}	1.7	4	Bi^{209}	2.5	7, 8
Sr^{87}	1.9	4	Th^{232}	3.6	10
Sr^{88}	2.0	4	U^{238}	3.6	10

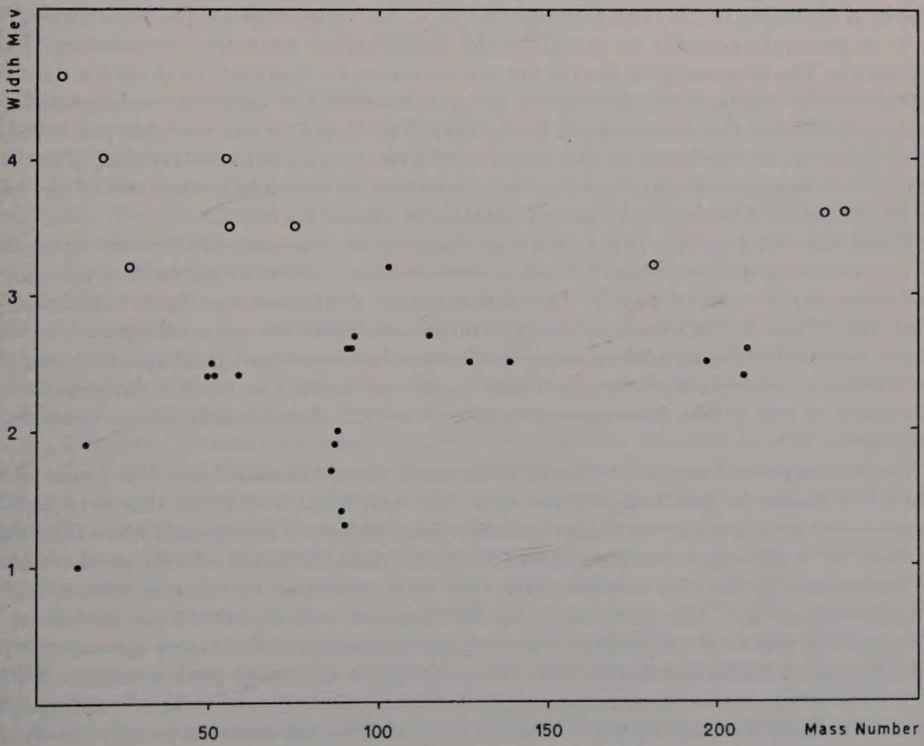

Fig. 1. The data of Table 1 plotted against the mass number. Black dots denote non-deformed nuclei, open circles deformed nuclei.

narrowest resonance. It has also the highest threshold, 12.3 Mev. Next comes Y^{89} with the threshold at 12 Mev and Sr^{86} with the threshold at 11.5 Mev. In general, a high threshold means a narrow resonance and vice versa. This fact suggests the following explanation for the dip at N = 50. The (γ,n) reaction is predominant for these nuclei but the (γ,p) reaction is not negligible. The yield of protons is 10–20 % of the neutron yield (14). The threshold for the (γ,p) reaction is rather low. Below the (γ,n) threshold, (γ,p) is therefore the major reaction. Above the (γ,n) threshold proton emission should be able to compete very strongly with neutron emission for an energy range of 2–3 Mev. This means that the (γ,n) cross-section curve is depressed in its low energy part. Hence, even if the total cross-section curve is not especially narrow, the high threshold will make the (γ,n) curve narrow. This is a secondary effect, not directly related to the photon absorption. The other nuclei with magic N do not have an especially high neutron threshold and the widths are the same as for neighbouring nuclei. Hence the claim that the magic nuclei have a narrow resonance does not seem to be supported by the experimental data.

The most interesting feature of Fig. 1 is the fact that there is complete separation between deformed and non-deformed nuclei. The non-deformed nuclei form a fairly uniform group. The exceptions are the dip at N = 50 and some light nuclei, especially C^{12}. The deformed nuclei have widths which in the mean are about 1 Mev larger. Some of them, like Li^7 and F^{19}, have a very broad resonance.

Hence the suggestion that the giant resonance in deformed nuclei is broadened due to a splitting in two components seems to be supported by the data in Fig. 1. It is in principle possible to calculate the deformation from the broadening of the resonance. The cross-section curves are not so accurate, however, that such a detailed calculation is warranted. Instead we have calculated the shape to be expected for various values of the deformation parameter. The width of the two components has been taken to be the same as the mean width of the non-deformed nuclei. The ratio of the two resonance frequencies has been assumed to be equal to the ratio of the axes in the ellipsoid. The result of this calculation is shown in Fig. 2.

When the deformation is 0.4, the two components become rather well separated. It is interesting to note that F^{19} has a cross-section curve which is very similar to the curve for $\delta = 0.4$ in Fig. 2. The deformation of fluorine has been calculated to 0.39 (15). When $\delta = 0.3$ the low energy component gives rise to a bump on the resonance. Some of the measured cross-section curves have exactly this shape, for example, the thorium and uranium curves. These nuclei are known to have a deformation of the order of 0.3. If the deformation is as low as 0.2, there is only an asymmetry in the curve.

The assumption that the two components of the resonance have the same width should of course be justified in some way. One empirical way to do this is to look at some nuclei that are known to have a large deformation. They should have the cross-section curve split up to such an extent that it is possible to get a fairly good estimate of the widths of the two components. One such example, mentioned above, is F^{19}. Another one is Be^9. The (γ,n) curve for Be^9 has two well-separated peaks, one at 10 Mev and the other one at 22 Mev. The general behaviour of the curve agrees with the calculations of Guth and Mullin (16). They interpret the lower peak as due to a *P–D* transition of the outer neutron. It seems, however, that the curve can be interpreted equally well on the basis of the collective nmodel. The deformation parameter should then be of the order of 0.5, which is a reasonable value. If the curves for Be^9 and F^{19} are analysed, it turns out that widths of the two components are about the same and

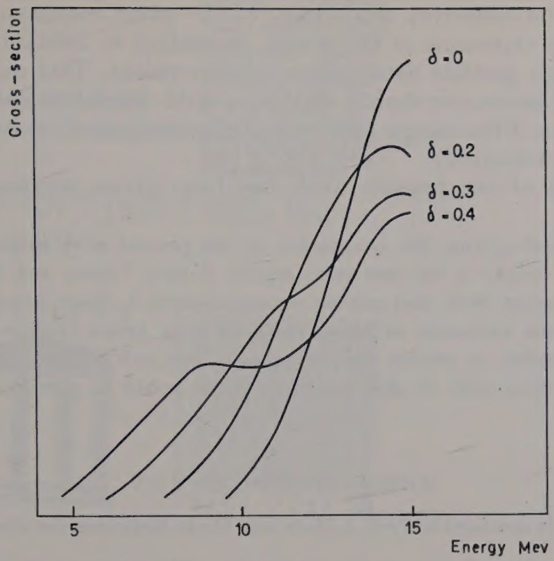

Fig. 2. The general shape of the cross-section curves for different deformations calculated on the basis of the assumptions given in the text. The energy of the high energy component has been taken to be 15 Mev.

approximately equal to the width for the non-deformed nuclei. This fact gives some support for the assumptions underlying Fig. 2, at least for the light elements.

Strongly deformed nuclei are known to exist mainly in two regions, $150 < A < 190$ and $A > 222$. Some light nuclei around $A = 25$ and $A = 8$ are very probably also deformed. According to the criterion used in the present discussion other nuclei should also have a stable deformation, for example, Mn^{55} and As^{75}. There is some experimental evidence for this assumption. They have a fairly large quadrupole moment. The spin of Mn^{55} is anomalous on the bais of the shell model but can easily be explained on the assumption of a deformation. For the purpose of the present discussion it is perhaps not necessary, however, to assume that these nuclei are deformed in the gound state. They should at any rate be rather "soft" against a deformation. It might be that in this case the nucleus is deformed in the excited state. It remains to be investigated, however, if there exists any coupling of sufficient strength between the dipole oscillations and the shape of the nucleus. Another possibility is that these soft nuclei perform shape oscillations with a fairly large amplitude. They would then have a mean deformation, which would split up the giant resonance.

It is interesting to note that the non-deformed nuclei have a rather constant width with surprisingly small deviations from the mean value, except for the special cases $N = 50$ and some very light nuclei. Another exception is Rh^{103}. This nucleus lies, however, very close to the limit according to the criterion quoted above. The constant width for non-deformed nuclei is in agreement with theoretical calculations [17, 18]. The points for the deformed nuclei scatter considerably, which is a natural consequence of the variations in deformation. Another interesting feature is that there seems to be a gap between the deformed and non-deformed nuclei. This might be due to the fact that there is a minimum value for a stable deformation.

It seems that the collective description of the giant resonance gives a natural explanation of the variations of the width. According to Brink (18), however, the collective and single particle descriptions are equivalent. This would indicate that the spliting of the resonance should also occur with the latter description. In fact, this seems to be true if the energy levels for a deformed potential are used (B. Mottelson, private communication).

A brief account of the present work has been given previously (19).

Note added in proof.—After the completion of the present work some new measurements have been reported, mainly in the rare earth region (Fuller, Petree, and Weiss, National Bureau of Standards Report 5686, and private communication; L. Katz, private communication). As expected the giant resonance of these nuclei is very broad. Fuller *et al.* report that in some cases it is possible to resolve the resonance in two well separated peaks but Katz did not find this effect. More work on this important point would be particularly interesting.

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